buckled or collapsed, intruding into the occupant survival space.[10] In some cases, an occupant was injured by the collapsing roof and subsequently ejected.

The failure of side window glazing, which permitted Ms. Raley's ejection from the vehicle, is a consequence of both the distortion of the window frame in the driver's door and the use of tempered glazing for side windows. We have found both in tests we have conducted and in analyses of other data that if there is less than roughly 3 to 4 inches of roof distortion, even tempered side glazing is unlikely to break. However, only a combination of retained laminated glass for side windows and limited distortion of the window frame can generally ensure that the side window opening will not become an ejection portal for occupants.[11]

Rollover Accident Data

Between 1995 and 1999, according to NHTSA, 10,149 annual average deaths which represent more than 31% of all light vehicle occupant fatalities, occurred in rollovers. Nearly all of these rollovers involve roof deformation or open portals for ejection. Today, rollover fatal and serious injury rates per total occupants are over three times higher than for frontal and all other accident modes combined.[12]

Currently, more than 418,000 occupants are involved in more than 253,000 vehicle rollovers annually. Of these, approximately 378,000 are not seriously injured. Of the remaining 40,000 occupants, 30,000 are seriously injured and more than 10,000 are fatally injured.[13] Approximately 6,900 of those non-ejected though seriously or fatally injured are known to have received their injuries from roof contact.[14]

A similar pattern of vehicle damage has been seen in the more than 600 rollovers investigated by this office. Typically the vehicle roofs collapse laterally and inwardly into the occupant compartment as a result of loading in the vicinity of the junction of the A-pillar, roof rail and windshield header. Amongst light trucks and SUVs, this pattern is similar across all manufacturers' product lines and is a result of the common geometry shared by these vehicles.

Roof Performance in Rollovers

A modern light vehicle roof is constructed primarily of mild steel sheet that has been pressed into structural elements and panels, and spot welded into a single unit. Some strength; on the order of 30%, particularly against lateral shear; is provided by the laminated glass windshield which is held in place in the steel structure by strong adhesives. The strength of the roof is compromised in many designs by open sections (which is significantly weaker than a box

[10] Malliaris, A.C., et al., "A Search For Priorities in Crash Protection," SAE 820242.

[11] Willke, Donald, et al., "Ejection Mitigation Using Advanced Glazing," NHTSA Final Report, August 2001

[12] Federal Register, Vol. 66, No. 204, Roof Crush Resistance, NHTSA Docket-1999-5572, Notice 2, October 22, 2001.

[13] "Initiatives to Address the Mitigation of Vehicle Rollover" National Highway Traffic Safety Administration, Washington, D.C.: June 2003

[14] Federal Register, Vol. 66, No. 204, Roof Crush Resistance, NHTSA Docket-1999-5572, Notice 2, October 22, 2001.

section), by holes in critical structural elements, by inadequate overlap of structural elements, particularly around the top of the A pillar, and by inadequate welds (which are typically about 1 inch apart).

Failures of roofs under ground impacts result from (1) the failure of the windshield glazing or its attachment to the roof structure, (2) buckling at weak points of the roof (holes, open sections, ends of structural elements), and (3) structural material of inadequate inherent strength (either material that is too thin or that is mild rather than high strength steel).

When a vehicle rolls, it typically pitches forward so that the front corners of the roof are the primary points of contact. This is demonstrated by the fact that the front fenders of vehicles that have rolled over show patterns of scratches or other damage indicating that they were in contact with the ground.[15]

The first contact with the initially leading (near) side of the roof does not generally produce significant roof distortion both because the windshield still contributes to its strength at this point and because the force vector of this contact is generally parallel to the vertical axis of the vehicle in which the roof is strongest. The second contact, or the first contact with the initially trailing (far) side of the roof does typically break the windshield and precipitate the failure of its adhesive attachment to the roof structure.

Contact of the far side of the roof is more likely to distort the roof because, as the vehicle rolls over on its side, the force vector is more lateral with respect to the vehicle.[16,17] This effectively reduces the roof's strength-to-weight ratio (SWR), on average, by nearly 60 percent in impacts subsequent to windshield failure. For a vehicle that fully complies with FMVSS 216, roof strength can be less than half that measured in testing to that standard. On subsequent rolls the roof, now weakened by the loss of windshield contribution, typically crushes extensively on the far side.[18] The greatest crush usually occurs on later rolls because the vehicle's roll velocity has slowed so that the roof dwells on the ground for longer.

As a vehicle rolls, its center of gravity rises about one foot initially as the vehicle goes up on two wheels. After that, until the vehicle comes to rest, the center of gravity rarely rises or falls more than a few inches, so that the roof impacts result from a fall of no more than about 6 inches on any roof impact. The result is that that the roof's impact speed is less than about 5 feet per second – slightly greater than a person's walking speed.

It has been widely recognized since at least the late 1960s that the two factors that produce most rollover occupant injuries are roof crush and occupant ejection.

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[15] Nash, Carl E. and Allan Paskin, "A Study of NASS Rollover Cases and the Implication for Federal Regulation," Experimental Safety Vehicle Conference, Washington, D.C. June 8, 2005, Paper # 05-0415-O

[16] "Cab Roof Crush – Rollover Simulation," GM Inter-Organization Document from I. Arums to J.D. Green, June 27th, 1984.

[17] Friedman, D. and Nash, C. E., "Measuring Rollover Roof Strength for Occupant Protection", 2002 International Crashworthiness Conference, ICRASH 2002, February 25 – 27, 2002, Melbourne, Australia.

[18] Mahadevan, K., Zhoe, J., Cohen, K.A. and Sambandam, S., "Roof Crush Variability Study Using FEA and DOE," Ford Internal Document, December 12, 1994

These facts about rollovers come from analyses of dolly rollover tests conducted by GM, Ford, and their contractors. In particular, the Malibu tests (discussed in a later section) provide substantial insight into the performance of vehicles with weak and strong roofs in rollovers.

Federal Standards and Evaluation

Rollover casualties have been a focus of government regulation and of litigation for almost forty years. In the 1960s, it was recognized that the two causes of occupant injury in rollovers were that unrestrained occupants were being ejected and that occupants were being injured from roof buckling and collapse into the occupant survival space[19]. In some cases, the occupant was both injured by the collapsing roof and subsequently ejected.

In 1967, the NHSB (National Highway Safety Bureau, the precursor to National Highway Traffic Safety Administration or NHTSA) promulgated Federal motor vehicle safety standards (FMVSS) 208, 209 and 210 setting standards for lap and shoulder belts[20]. In 1970, as part of a program to make FMVSS 208 a more comprehensive crash protection standard, it was amended to include dynamic dolly rollover testing[21]. According to NHSB, in 1969 approximately 1,400 automobile occupant fatalities, about 5% of the total, were due to the roof structure contacting the occupant during a rollover.[22]

Because of objections that the rollover test in FMVSS 208 did not produce repeatable results,[23] this requirement was made optional before it became effective.

In the late 1960s, General Motors developed a roof crush test that was adopted by the Society of Automotive Engineers as Recommended Practice J374. It uses a flat platen, 6 feet long and 1½ feet wide, to load the roof at a roll angle of 25° and a pitch angle of 5° on the front corner of the roof. The force is monitored as the platen is pressed through a displacement of up to 5 inches.

NHTSA conducted a test series and developed a modified test protocol that it proposed as FMVSS 216 in which a 1 foot square platen is pressed at a roll angle of 25° and a pitch angle of 10° on the front corner of the roof of the first side of the vehicle until a force of at least 1.5 times the vehicle weight is reached or a displacement of 5 inches is reached. The test was then repeated on the second side of the vehicle (with no repairs permitted). The vehicle passes if it can sustain a force of 1.5 times the vehicle weight before a displacement of 5 inches is reached on each side.[24]

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[19] Malliaris, A.C., et al., "A Search For Priorities in Crash Protection," SAE 820242.
[20] Code of Federal Regulations, 49 CFR Ch. V, Sections 571.208 through 210.
[21] Ibid. The dolly rollover test is conducted by carrying a vehicle laterally on a dolly at a roll angle of 23° and a speed of 30 mph. The dolly is arrested, and the vehicle moves off, typically rolling about three complete rolls. The vehicle passes this test if no part of an unrestrained dummy within the vehicle is ejected.
[22] Federal Register, Vol. 36, No. 3, January 6, 1971.
[23] The objection was specious in that a vehicle that could pass (i.e. one for which the doors remained closed and the windows did not break) could do so repeatedly regardless of the number of rolls.
[24] Federal Register, Doc. 71-17936, December 7, 1971.

In the 1971 rulemaking, GM and Ford strongly objected to the proposed test, but provided no technical or scientific arguments.[25] NHTSA bowed to industry pressure and adopted the test procedure of SAE Recommended Practice J374 as FMVSS 216. That procedure used a much larger platen at a 5° pitch angle, and tested only one side of the roof.[26,27] The introduction of a larger platen and shallower pitch angle ensured that the force would be absorbed by both the A and B-pillars in the test which increases the load carrying capacity of the roof by approximately 40%.[28] It was subsequently learned that these companies had tested a number of their own vehicles to the proposed standard, and all but one failed.[29,30] The companies never disclosed these tests to the government, however. NHTSA also included a 5,000 pound limit on the force if the vehicle weighed more than 3,333 pounds. The agency continued to state that rollover occupant protection was related to roof crush.[31]

NHTSA also rationalized that the standard would be in place for only a few years before the dolly rollover requirements of FMVSS 208 became effective, however, that never happened.

Following the effective date of FMVSS 216, roof contact deaths in rollovers continued to increase. In 1980, rollover fatalities accounted for more than 5,000[32] fatalities or over 10%[33] of all automobile occupant fatalities. FMVSS 216 was extended to light trucks and vans (LTVs) including sport utility vehicles (SUVs) beginning with the 1994 model year[34] despite the fact that NHTSA's 1989 evaluation of the standard showed that it had no significant impact on passenger car safety[35]. The only concession was to eliminate the 5,000 pound force limit for LTVs, but the standard was limited to LTVs with gross vehicle weight ratings under 6,000 pounds. Light trucks' rollover propensities are approximately 2 ½ times higher than automobiles[36,37] and they have lower rollover stability ratings in NHTSA's New Car Assessment Program (NCAP) [38].

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[25] General Motor's Comments on Notice of Proposed Rule Making, Docket2-6, Notice 4 – Roof Intrusion Protection for Passenger Cars, April 5, 1971.

[26] Federal Register, Doc. 71-17936, December 7, 1971.

[27] General Motor's Comments on Notice of Proposed Rule Making, Docket2-6, Notice 4 – Roof Intrusion Protection for Passenger Cars, April 5, 1971.

[28] "GMT-400 Static Cab Crush Results," GM Internal Document from J.W. Moll to M.O. Ellis, January 28, 1987.

[29] General Motors Product Test Report No. 111037, Subject: Bodies – Static Roof Intrusion Tests – 1970 and 1971 F, H, A, X, and B Styles, D.E. Foley, March 5, 1971. All bodies tested except the X-27 failed to meet the requirements of the proposed roof crush test requirements (Docket 2-6, Notice 4).

[30] Ford Test No. 20, *Roof Crush Program* 1970 Model 65 Ford Production Car, January 21, 1971; Ford Test No. 23, *Roof Crush Program,* 1971 Model 65 Ford Production Car, January 27, 1971; Ford Test No. 28, *Roof Crush Program,* 1968 Model 57 Ford Production Car, February 19, 1971; Ford Test No. 27, *Roof Crush Program,* 1968 Model 57 Ford Production Car, March 5, 1971.

[31] Federal Register, Vol. 36, No. 236 – Part 571 – Motor Vehicle Safety Standards 216, December 8, 1971

[32] *Kahane, C.J., "An Evaluation of Door Locks and Roof Crush Resistance of Passenger Cars," NHTSA Report Number DOT HS 807 489, November, 1989.*

[33] *2000 NHTSA Traffic Safety Facts*

[34] Federal Register, Vol. 56, No. 74, Rules and Regulations, NHTSA Docket 89-22; Notice 3, April 17, 1991.

[35] Kahane, C.J., "An Evaluation of Door Locks and Roof Crush Resistance of Passenger Cars," NHTSA Report Number DOT HS 807 489, November, 1989.

[36] "Traffic Safety Facts 2001," NHTSA, DOT HS 809 476, pg 10.

[37] "An Overview of the Field Accident Experience of Light Trucks and Vans," GM Internal Study, 12/10/1979, pg. 1.

[38] NHTSA, NCAP Star Ratings.

Rollover casualties in pickups and SUVs have continued to increase dramatically since 1994 while fatalities in other accident modes have decreased[39].

In 1989, NHTSA evaluated the standard and showed that it had no significant impact on passenger car safety:

> All of the pre-Standard 216 cars met the minimum requirements of Standard 216 in that they had 'Minimum Roof Crush' less than 5 inches. The best performer was the 1964 Dodge Dart which achieved the required force level at 0.9 inches of crush."[40]

The evaluation further pointed out that:

> [a]nother characteristic of rollovers is that many of the fatal crashes do not involve great amounts of force or destruction to the car...rollover fatalities appear more easily 'savable' than some other types . . .[41]

The ineffectiveness of FMVSS 216 can be traced to automobile manufacturer's minimal efforts to comply with the static test of this standard. Automobile manufacturers generally meet even this weak standard by relying substantially on the windshield's strength and its bonding to the body. As long as the windshield and its bonding retain their integrity, the windshield typically provides up to 30% of the load carrying capacity of the roof. By the time the windshield fails, because of the shallow pitch angle specified in the standard, the B pillar picks up a sufficient part of the load to ensure compliance. NHTSA initially proposed that FMVSS 216 have a 10 degree pitch angle, but this was reduced to 5 degrees because of protests from General Motors and the automotive industry even though investigations of rollovers show that a rolling vehicle typically is pitched at 10 degrees during the rollover.[42] This is an inexpensive method of satisfying FMVSS 216, but it provides little real protection in the most hazardous rollovers: those in which there are multiple roof impacts.

Compliance with FMVSS 216 generally ensures that a LTV's first contact-side roof, with the windshield glass bonded in place, will not collapse excessively. However, subsequent roof impacts are not regulated by any Federal standard. In a multiple-roll rollover, the windshield almost always breaks or loses its bonding to the structure on the first roll. The roof strength on subsequent impacts is only about 40% of what is measured on the regulated first contact-side under FMVSS 216 due to both the loss of the windshield and the lateral loading associated with second contact side roof to ground impacts.

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[39] "Traffic Safety Facts 2001," NHTSA, DOT HS 809 476, pg 10.

[40] Kahane, C.J., "An Evaluation of Door Locks and Roof Crush Resistance of Passenger Cars," NHTSA Report Number DOT HS 807 489, November, 1989.

[41] Ibid.

[42] Nash, Carl E. and Allan Paskin, "A Study of NASS Rollover Cases and the Implication for Federal Regulation," Experimental Safety Vehicle Conference, Washington, D.C. June 8, 2005, Paper # 05-0415-O

Current Roof Strength Regulatory Activity

NHTSA's investigation into the inability of FMVSS 216 to protect occupants from serious injury and death in rollover crashes continues today. In October of 2001 the agency asked for comments concerning a possible upgrade to the roof crush standard. Following a nearly four-year comment period the agency released a notice of proposed rule making (NPRM) in August 2005 in which it announced it was increasing the requirement for roof crush resistance form one and one-half (1.5) times the vehicle weight to two and one-half (2.5) times.[43] The agency recognizes that automobile manufacturers typically build in a twenty percent margin to insure compliance so this effectively means that vehicles will have roofs that are three (3) times their weight.

In support of the NPRM, NHTSA uses a cost basis for choosing the force requirement for the test. The cost of compliance with the new standard estimated by NHTSA is $10.67 per vehicle.[44] Higher levels of protection can be achieved at a higher cost, but the agency did not think the per-life cost was justified. While this increase in required roof strength is a step in the right direction it too will fail to adequately protect occupants from the crushing of the roof into the passenger compartment during rollover crashes. The deficiencies of the proposed upgrade to FMVSS 216 and how to adequately address them are set forth in detail in CAS, CFIR and Xprts, LLC comments to Docket No. NHTSA-2005-22143.

This upgrade was made in acknowledgement of the fact that occupants with negative post-crash headroom had five times the odds of a particular level of injury severity than an occupant with positive post-crash headroom.[45] This clearly illustrates the importance of sustaining occupant survival space in rollover crashes as in all other crash modes. This agrees with experimental crashworthiness tests conducted by the automotive industry[46],[47],[48] in which it was clearly shown that weak roof vehicles were much more dangerous than strong roof vehicles, confirming what the automobile manufacturers have known for more than seventy years: strong roofs protect occupants in rollover crashes.

Rollover Testing and Research

There are a number of tests that are routinely used to evaluate the rollover and roof crush performance of vehicles. They include the following:

Early Tests. In the 1930s, GM and Chrysler conducted rollover tests in which the vehicle was either pushed down the side of a hill or was driven in a J-turn so that it began to roll over. In

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[43] Department of Transportation, NHTSA, 49 CFR Part 571, Docket No. NHTSA-2005-22143, RIN 2127-AG51, "FMVSS; Roof Crush Resistance, August, 2005.
[44] Ibid, pg. 7.
[45] Austin, R., Hicks, M and Summers, S.; Office of Vehicle Safety, NHTSA, "The Role of Post-Crash Headroom in Predicting Roof Contact Injuries to the Head, Neck, or Face During FMVSS No. 216 Rollovers, August, 2005.
[46] Orlowski, K.F., Bundorf, R.T. and Moffatt, E.A., "Rollover Crash Tests – The Influence of Roof Strength on Injury Mechanics," SAE 851734.
[47] Bahling, G.S., Bundorf, R.T., Kaspzyk, G.S., Moffatt, E.A., Orlowski, K.F. and Stocke, J.E., "Rollover and Drop Tests – The Influence of Roof Strength on Injury Mechanics Using Belted Dummies," SAE 902314.
[48] Submission to NHTSA Docket 1999-5572 by Safety Research & Strategies, Inc, April, 2005.

the most dramatic and well-documented of these tests, a Chrysler AirFlow was driven in a J-turn on dirt and executed two complete rolls. The driver, who was seated in the initially trailing front seat, which is most dangerous seating position, was restrained only by a makeshift lap belt. He was uninjured, and the roof of the vehicle suffered only superficial damage to the roof panel. None of the vehicle windows broke.[49]

A 1936 test of a Dodge sedan was described in a Chrysler advertisement as follows:

> In a dramatic demonstration of the structural integrity of the 1936 Dodge, W.E. Blandenburg straps himself into the car and rolls it down a steep embankment. Incredibly, the car lands right side up. Even more incredibly, Blandenburg gets out, smiles for the cameras, gets back in and drives away.[50]

Pictures of the vehicle in the ad show little or no damage to the roof.

GM conducted tests of its Chevrolet vehicles in which they were pushed sideways down a steep hill. Following the multiple rollover, the roofs of these vehicles retained their basic integrity.[51]

FMVSS 216. This quasi-static roof crush resistance test was described in detail above. The deficiencies in this standard are that (1) the force is inadequate to emulate the force on a vehicle in an actual rollover, (2) the roll angle does not emulate the more lateral force angle in the impact of the far side of the roof, (3) the test does not emulate the effect of multiple roof impacts that are typical of rollovers that result in occupant injury, (4) the shallow pitch angle (5°) and very long platen permit the B pillar to take up an unrealistic part of the force on the roof.

FMVSS 208 dolly rollover. Just before NHTSA proposed a comprehensive passive occupant protection standard, FMVSS 208 that included a dolly rollover test. In that test, the vehicle is carried laterally at a roll angle of 23° and a speed of 30 mph. The dolly is rapidly halted, the vehicle flies free and begins a rollover that typically is 2 to 4 rolls. The criterion for passing this standard is that no part of an unrestrained dummy carried in the vehicle can be ejected. The standard remains on the books, but is an optional compliance procedure.

Although there have been ongoing complaints that the dolly rollover is not an adequately repeatable and reproducible test, in the lawsuit *Chrysler v. DOT* , the Sixth Circuit Court of Appeals declared that it was. Furthermore, the test is widely used even within the auto industry.[52] Our professional opinion is that the variable results in dolly rollover tests are a function of the variations in production cars rather than a lack of repeatability of the test.

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[49] Chrysler Corporation promotional film of the 1934 AirFlow

[50] "Possibly the Only Time Anybody Got Ahead by Playing it Safe," Chrysler Corporation advertisement, *Automotive News,* September 21, 1993, p. 156

[51] *History of Rollover*, video of old General Motors rollover tests.

[52] See, for example, Ford SUV Test 1 (Autoliv Test B190042) conducted 8/10/99; Ford SUV Test 2 (Autoliv Test B180219) conducted 12/9/98; Ford SUV Test 3 (Autoliv Test B190043) conducted 8/11/99; and Ford SUV Test 4 (Autoliv Test B180220) conducted 12/10/98. General Motors has announced the construction of a major dolly

The Malibu Tests. In 1985 General Motors Corporation (GMC), along with a former employee and current product liability defense litigation consultant, wrote a paper entitled *Rollover Crash Tests – The Influence of Roof Strength on Injury Mechanics*[53] that was published by the Society of Automotive Engineers (SAE). This study investigated the effect of roof strength on unrestrained occupant injury in dolly rollover tests. The data collected from this series of eight rollovers (four roll caged vehicles and four production roof vehicles) show that occupant injury only occurs when there is roof crush and associated buckling and failing of roof support structures. Absent such roof crush and structural failures the unrestrained test dummies in the vehicles did not register injury values that could be correlated with a risk for serious or fatal injury to humans. In fact, so long as the dummies were not under a portion of the roof that was collapsing (by virtue of being able to tumble about the interior of the vehicle unrestrained) no serious injury measures were recorded even in the dummies in the production roof vehicles.

A second study by GMC and its litigation consultants, *Rollover and Drop Tests – The Influence of Roof Strength on Injury Mechanics Using Belted Dummies*[54], was published by the SAE in 1989. The test regime was identical to the first study (four roll caged vehicles and four production roof vehicles) with the exception that the test dummies were restrained with a three-point seatbelt that utilized a cinching latch plate. The data from this study clearly identified the risk of catastrophic injury to restrained occupants in production roof vehicles where the roof buckled, crushed and failed over the occupant survival space. GMC's own analysis showed that when the injury criterion was set at a realistic level the only potential injuries occurred in production roof vehicles. Dummies in roll-caged vehicles never recorded injury measures suggestive of serious to the head or neck.[55,56,57]

GM measured various parameters of rollovers, including the falling speed of rolling vehicles, and they were extensively filmed. The results of the Malibu tests were confirmed in subsequent analyses of dynamic rollover tests conducted on other manufacturers' vehicles. The tests showed that excessive head and neck loads were sustained only by occupants of the vehicles without roll cages for both restrained and unrestrained occupants. We have analyzed the Malibu tests in detail. These tests demonstrate the mechanism of head and neck injury and relate it causally to the roof strength, crush and crush velocity.

Currently, there is no concurrence injury reference value in the automobile safety field for serious neck injury measurement in the Hybrid III test dummy in rollover crashes. A compressive neck load of 4,500 Newtons (4.4 Newtons = 1.0 pound) has been defined as an

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rollover test facility: Jeff Plunges, "GM will build $33 million Milford rollover test center," *Detroit News*, June 10, 2005.

[53] Orlowski, K.F., Bundorf, R.T. and Moffatt, E.A., "Rollover Crash Tests – The Influence of Roof Strength on Injury Mechanics," SAE 851734.

[54] Bahling, G.S., Bundorf, R.T., Kaspzyk, G.S., Moffatt, E.A., Orlowski, K.F. and Stocke, J.E., "Rollover and Drop Tests – The Influence of Roof Strength on Injury Mechanics Using Belted Dummies," SAE 902314.

[55] Malibu II data package at page MALIBU20000375, DUAN 000800698

[56] Sances A, Carlin F, Kumaresan S, *Biomechanical Analysis of Head-Neck Force in Hybrid III Dummy During Inverted Vertical Drops*, 38th Biomedical Sciences Instrumentation Conference, 2002

[57] Viano DC, Pellman EJ, *Concussion in Professional Football Player: Biomechanics of the Striking Player – Part 8*, Neurosurgery 56:266-280, 2005.

injury threshold for advanced airbag protection in frontal crashes.[58] However, studies have been conducted by a number of researchers that indicate for rollover crashes (and frontal crashes as well) the threshold is in excess of 4,500 Netwons.[59,60]

Mertz derived the 4,000 Newton reference value from an investigation of a small number of high school football player injuries.[61] These injuries occurred when the players were struck on their heads, while wearing a helmet, by a spring-loaded tackling dummy. These impacts resulted in cervical spinal fractures. Mertz impacted helmeted Hybrid III dummies with the same model tackling block that produced the injuries and recorded the neck loads. However, he did not calculate the delta-v of the head of the dummies.

Recent work studying National Football League players provides further insight into injury reference values for the Hybrid III dummy.[62] This study carefully photo-analyzed 27 impacts between players. He then recreated the impact conditions in the laboratory using helmeted Hybrid III dummies. The results of this study suggest that a more appropriate serious injury reference value is somewhere above 7,000 Newtons. Viano's work allows for the important correlation between neck load and head delta-v. It is unlikely that serious head and neck injury can occur with a change in velocity of the head less than 7 miles per hour.

Viano's findings support research done by other investigators with cadavers and the Hybrid III dummy.[63,64,65] Taken as a whole this body of research clearly proves that the onset level for catastrophic neck injury is somewhere in excess of 7 miles per hour and that such injuries likely occur at 10 mph or more. Relating these finding to the Malibu studies, and other rollover testing conducted for litigation and product development, demonstrates that if the occupant is contained in an environment where its head cannot experience a delta-v in excess of 7 mph, serious neck injury is unlikely to occur. As the Malibu tests prove such injurious delta-v do not occur in roll-caged vehicles. The tests also prove that Hybrid III dummies, whether restrained or not, do not fall to the roof with sufficient velocity to cause serious neck (or head) injury. It is only in production roof vehicles that the dummies in the Malibu tests were subjected delta-v and neck loads correlating to serious neck injury. This concept is illustrated and demonstrated in comments to NHTSA Docket 2005-22143 made by Xprts and the Center for Injury Research.[66,67]

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[58] Eppinger, R., et al. "Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems - II", NHTSA, November 1999.

[59] Viano, D.C. and Pellman, E.J., "Concussion in Professional Football Player: Biomechanics of the Striking Player - Part 8", Neurosurgery 56:266-280, 2005

[60] Bidez, M.W., Cochran, J.E. and King, D., "Roof Crush as a Source of Injury in Rollover Crashes", NHTSA Docket 5572, March 2005

[61] Mertz, H., Nyquist, G., et al., *An Assessment of Compressive Neck Loads Under Injury-Producing Conditions*, Nov. 1978

[62] Viano DC, Pellman EJ, *Concussion in Professional Football Player: Biomechanics of the Striking Player – Part 8*, Neurosurgery 56:266-280, 2005.

[63] Nusholtz GS, Huelke DE, Lux P, Alem NM, Montalvo F, *Cervical Spine Injury Mechanisms*, SAE 831616.

[64] Nightingale RW, McElhaney JH, Camacho DL, Kleinberger M, Winkelstein BA, Myers BS, *The Dynamic Responses of the Cervical Spine: Buckling, End Conditions, and Tolerance in Compressive Impacts*, SAE 973344.

[65] Sances A, Carlin F, Kumaresan S, *Biomechanical Analysis of Head-Neck Force in Hybrid III Dummy During Inverted Vertical Drops*, 38th Biomedical Sciences Instrumentation Conference, 2002

[66] CFIR's 2nd Submission to NHTSA Docket No. 2005-22143

In the Malibu tests, the most severe roof damage occurred in roof impacts when the vehicle had rolled about 210 °, i.e. 180° plus 30°. This is characteristic of how GM justified the 25° angle (from the vertical) that they developed for their drop test procedure. However, during a rollover event the force on the roof comes from the vehicle drop as well as the lateral friction force from the interaction between the relative motion of the vehicle and the ground. When these force components are combined, the net force vector of the Malibu roof impacts is at approximately the same angle as the quasi-static roof crush tests conducted on light trucks by GM in the mid 80's: 52° from the vertical (or 38° from the horizontal as described in published memoranda) and as in this office's lateral roof strength tests.[68]

This demonstrates that the actual force vector in typical, real-world rollovers is at a roll angle that is approximately twice that of FMVSS 216 (52° as opposed to 25° from the vertical), resulting in a more lateral load on the roof structure. Automobile manufacturers have long been aware of this fact.[69] In 1984, General Motors conducted a series of roof strength tests in which it applied the force at an angle of 52° rather than the 25° angle called for in FMVSS 216. In those tests, which included various light trucks from GM, Ford, and Toyota, GM found that the roof strength was decreased by roughly 40%.[70]

The resultant roof crush is inversely proportional to its strength. If the roof is strong, when it is subjected to an impact at an angle of around 52° with the vertical (38° with the horizontal), the vehicle will simply roll over the roof, raising the center of gravity of the vehicle to ride over the roof rail and increase its roll rate to match the translational velocity.

The Malibu tests document the non injurious head impact speeds as well as the injurious ones. No serious neck injuries occurred in Malibu sedans that had roll cages installed in them while four were measured using dummies seated on the initially trailing side of Malibu II production vehicles. The instrumentation used in these tests calibrated the extent of deformation with the speed of intrusion of panels and buckles, making clear that injury does not occur when the speed of impact or intrusion is less than about 5 mph.

Our office and others have evaluated 30 mph dolly rollover tests conducted on Ford Explorers by Autoliv (see below) and supplied by Ford in other litigation.[71] Analysis of this carefully instrumented testing makes it clear that the roof of the accident vehicle is of inadequate strength to protect its occupants in foreseeable rollover accidents and that the high neck forces follow and are caused by the collapse of the roof. We have also evaluated 30 to 50 mph dolly rollover tests conducted on Ford Explorers and Broncos, and General Motors Blazers to experimentally characterize higher speed SUV rollovers and their similarity to lower speed tests.[72,73,74,75,76]

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[67] Xprts' 1st Submission to NHTSA Docket No. 2005-22143
[68] "GMT-400 Static Cab Crush Results," GM Internal Document from J.W. Moll to M.O. Ellis, January 28th, 1987.
[69] Moffatt, E.A., "Occupant Motion in Rollovers," Proceedings of the Nineteenth Conference of the American Association for Automotive Medicine, Nov 20 – 22, 1975.
[70] "Static Cab Crush Results," GM Internal Document from J.W. Moll to M.O. Ellis, November 18th, 1985.
[71] Bidez, M.W., Cochran, J.E. and King, D., "Roof Crush as a Source of Injury in Rollover Crashes" NHTSA Docket 1999-5572-120, March 30, 2005.
[72] TEC 6072 1987 Chevrolet S-10 Blazer 50 mph Dolly Rollover and Photo Analysis (Production).

Automobile manufacturers maintain that the occupants of a rolling vehicle dive into the roof causing catastrophic injury. The Malibu tests showed that rolling vehicles and their occupants typically fall at about 3 mph and at not more than 5 mph when the roof of a rolling vehicle strikes the ground according to the GM Malibu tests. The 3- to 5 mph falling speed of the vehicle's center of gravity demonstrates that rollovers are not severe events.

Since the impacts are relatively benign, a structurally strong roof would preclude significant, rapid roof intrusion. A 3 to 5 mph head impact will not result in a serious head or neck injury. It is the rapidly intruding roof that produces the additional velocity and can cause injury in rollover accidents. Biomedical studies conducted with whole body cadavers and cadaver neck specimens have shown that velocities in excess of 7 mph and more typically greater than 10 mph are necessary to injure the human neck or cause a head injury.

The key role of roof deformation to serious injuries in rollovers has been reviewed in Rechnitzer & Lane[77] [1994]. From the review of published literature it was concluded that:

> In mass data and other crash collections, the weight of evidence is in agreement with a relationship between roof crush and occupant injury. There is a convincing relationship between rollover and spinal cord injury. Finally, there is strong evidence of a connection between local roof crush and spinal cord injury.

In regard to serious spinal injuries and roof crush, Rechnitzer et al[78] [1998] concluded that; "A strong argument can be made for the recognition of a causal relationship between roof crush and neck injury in rollovers."

Recently, the Volvo division of the Ford Motor Company, offered a view of the effects of roof crush on occupant protection that is at odds with the position espoused by the Ford in other litigation. The Volvo view, similar to our own, is that roof crush does matter. In an article published in *Forbes* magazine[79], a Volvo representative is referenced as saying:

> Finally, boron-steel members are used in the roofs of all Volvos to prevent the top of the car from pancaking, since, obviously, according to Nilsson (director of Volvo's Safety Centre), preventing spinal and head injuries is a lot easier when the integrity of the cockpit is maintained…

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[73] TEC 7124 1987 Chevrolet S-10 Blazer 50 mph Dolly Rollover and Photo Analysis (Rollcaged).
[74] 1989 Blazer 55 mph Dolly Rollover Video.
[75] 1996 Ford Explorer 51.2 mph Dolly Rollover Video.
[76] 1978 Bronco 50 mph Dolly Rollover Test Video.
[77] Rechnitzer G., Lane J. (1994) 'Rollover Crash Study - Vehicle Design and Occupant Injuries', Monash University Accident Research Centre, Melbourne, Report No 65
[78] Rechnitzer G., Lane J., McIntosh A.S. & Scott G., Serious neck injury in rollovers – is roof crush a factor? International Journal of Crashworthiness, V3 No.3, Woodhead Publishing, Cambridge, U.K. September, 1998
[79] Forbes.com, "Safety Sells," dated 6/17/2002.

In testing over 50 vehicles, we have found that under more realistic lateral loading, the roof can resist little more than one third of the forces that are reported by manufacturers performing the FMVSS 216 test. The fact that this vehicle's roof cannot resist catastrophic buckling, collapse and intrusion into the occupant compartment under common and easily foreseeable accident conditions constitutes a safety defect in this vehicle. It is particularly egregious in a vehicle class that has a rollover fatality rate that is three times that of traditional passenger cars.

Not all vehicles are *known* to have this defect. We can only discuss those we have tested: about 50 models out of the entire fleet. We only analyze cases with catastrophic injuries, and have not had the opportunity to test vehicles with roofs that do not intrude rapidly under rollover conditions.

Other Contributing Factors: Secondary Defects

Interior Padding. Since the early part of this decade, all light motor vehicles have been required to have padding in head impact areas of the roof to reduce the potential for head injuries in crashes. The technology and materials for such padding has been well known for decades, and was used in some General Motors vehicles in the 1980s.[80] We have found in other vehicles that the padding masks the traditional witness marks. Such locations can only be detected when blood or hairs are adhering to the surface, or when the trim and liner are removed from the vehicle for inspection. With the longitudinal buckle producing massive roof crush over the driver's seating position in this case, the FMVSS 201 interior padding probably would have had little effect on Ms. Raley's injuries, but had the roof crush been limited, the interior padding would have contributed to protecting her head and neck.[81],[82]

Alternative Design

The purpose of FMVSS 216 is stated as:

> "The purpose of this standard is to reduce deaths and injuries due to the crushing of the roof into the occupant compartment in rollover crashes."[83]

Failure to meet this clear intent of FMVSS 216 produces an unreasonably dangerous vehicle, and constitutes a conscious disregard for public safety in a foreseeable rollover. For rollover protection, the roof structure is primary to providing good rollover occupant protection. It should be designed and constructed so as to minimize intrusion into the occupant compartment.

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[80] List of known GM vehicles that had metal air gap padding
[81] McLean, AJ, et al., "Prevention of Head Injuries to Car Occupants: An Investigation of Interior Padding Options," Federal Office of Road Safety, Australia, CR 160 (FORS), 1997
[82] Monk, Michael, et al., "Energy Absorption Material Selection Methodology for Head/A-Pillar," SAE 861887
[83] Code of Federal Regulations, 49 CFR Ch. V, Sections 571.216.

In past litigation, we have drop tested a production and reinforced Mazda B2300 Pickup, a sister to the Ford Ranger, at the angles most likely to replicate the dynamic conditions experienced by the vehicle's roof in a rollover event. While the B2300 is not a sister or clone of the Hyundai Sonata, this test demonstrates the positive effect which simple reinforcement has on roof strength in rollover conditions.[84] If the same simple modifications had been built into the Raley vehicle, then Ms. Raley probably would not have sustained fatal injuries.

The modified B2300 pickup was reinforced with a non-optimized 16 pound steel roll structure to achieve a SWR of 1.6 under rollover conditions.

In 1990, GM comments to NHTSA Docket 89-22, Notice 1 claimed that to meet the proposed FMVSS 216 requirements, "Cost and weight impact per vehicle are estimated to be an additional $9.00 and 5 pounds respectively for both the S/T and C/K truck lines."[85] They also suggested this could be accomplished by increasing the gauge thickness of various roof components. Since steel costs about $0.35 per pound, this would be a small cost penalty of $10 to $20.

In the Malibu I series of tests, General Motors added a non-integrated, non-optimized rollover structure weighing 160 pounds to the 1983, 3000 pound Malibu vehicle. This resulting roof structure resisted 24,000 lbs with less than 3 inches of deformation for a SWR of more than 8 in FMVSS 216 testing.[86] In other words, the roof structure was more than eight times stronger than the vehicle weight.

Feasible alternative designs to improve the roof strength of the accident vehicle include adding padding to the interior of the cab, filling the A-pillars with structural foam, integrating metal air gaps into the roof structure, using larger sections for structural members, or using higher strength materials. Any combination of these strengthening methods can be used to provide the necessary roof strength to protect occupants from reasonably foreseeable rollover accidents.

Tests conducted by our office have also proven that steel roll bar structures offer a relatively inexpensive and effective way to improve a roof's crush resistance. In addition, finite element analysis can be performed on a roof structure in the design phase relatively simply to determine which members should be altered by increasing gauge thickness or by modifying the section modulus.[87,88,89]

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[84] Friedman, D. and Nash, C. E., "Measuring Rollover Roof Strength for Occupant Protection", 2002 International Crashworthiness Conference, ICRASH 2002, February 25 – 27, 2002, Melbourne, Australia

[85] GM Response to Docket No. 89-22, Notice 1, FMVSS 216, Roof Crush Resistance, dated May 14, 1990

[86] Orlowski, K.F., Bundorf, R.T. and Moffatt, E.A., "Rollover Crash Tests – The Influence of Roof Strength on Injury Mechanics," SAE 851734

[87] Friedman, K. and Mobrem, M., "Vehicle Structural Design Utilizing Optimized Finite Element Modeling" SAE 981013.

[88] Friedman, K., Bish, J., Rogers, C., and Mobrem, M., "Improvements in Vehicle Crashworthiness through the use of Optimized Finite Element Modeling," International Symposium on Automotive Technology and Automation, June 14th – 18th 1999.

[89] "Roof Crush Variability Study Using FEA and DOE," Ford Internal Document by Mahadevan, K., Zhoe, J., Cohen, K.A. and Sambandam, S., December 12, 1994.

Any combination of these design alternatives would have protected Ms. Raley from her injuries from this accident.

Other manufacturers take a markedly different approach to designing a SUV. Volvo, a wholly owned subsidiary of Ford Motor Company, produced its first SUV, the XC90, in the 2003 model year. In the design of this vehicle, they conducted three dolly rollovers of S80 sedans (the XC90 was developed from the S80 platform) to investigate the effects of roof strength, seatbelt pre-tensioners, and side curtain rollover-triggered airbags. This test series exemplifies the crashworthiness testing that should be conducted to ensure that a vehicle can protect its occupants during a rollover. Videos illustrate the performance of the XC-90 in a dolly rollover test.[90] In these videos, the roof does not crush and the dummies are retained in the vehicle. These tests also quite clearly indicate that a strong roof is effective in preventing injuries.

The first test was conducted on a production S80 with HIII test dummies in the front and rear right seats.[91] The dummies were all restrained with the production belts systems. The test was a lateral rollover at 30 mph conducted according to FMVSS 208 with the passenger side leading. The far side (driver) dummy exceeded the test limits in neck compression with a measured load of 5,000 N (1124 lbs) with contact marks on the roof rail and grab bar. The report stated, "The driver's head was at 852 ms powerfully hit by roof and upper door frame. At 2374 ms caused large deformations of left A-pillar and roof again by high head accelerations. At this time, the head was hit by the curb handle." It added, "Both head hits led to severe neck loads."

Results for the passenger dummy include, "due to the fact that the car body deformations, at right side, were minor, the neck loads were also minor."

The summary of the test quite clearly states that, "1. Left A-pillar and the upper windshield frame, heavily deformed. 2. High loads on the driver dummy's neck. (Caused by the previous points.)"

Recommendations from the test include reinforcing various roof components, utilizing laminated side windows and activating belt pretensioners in the rollovers.

The second test in the series is of a reinforced vehicle and is referenced in the third test.

The third test in the series was similar to the previous two tests with HIII test dummies in both front seats, two pretensioners for the driver, a shoulder belt pretensioner for the passenger and no structural reinforcements.[92] The test results included:

> The vertical movement of the far side dummy (with buckle pretensioner) was substantial reduced in relation to the near side dummy's movement (without buckle pretensioner).

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[90] Volvo XC-90 Dolly Rollover Test Video, released with a Press Kit at the introduction of the XC90 in 2002.
[91] Volvo Test Report No 256272 titled "Lateral rollover at 30 mph according to FMVSS 208, Test No 98325.
[92] Volvo Test Report No 262279 titled "Lateral rollover at 30 mph according to FMVSS 208, Test No 003048.

> The vertical neck force Fz was in spite of that higher for the far side dummy due to more roof deformation on that side."
>
> The comparison with previous S80 rollover clearly shows how important the roof strength is for the occupant criteria. The roof structure in this test reinforced to estimate P28 strength. Maximum Fz-value for the far side was then only 0.7kN. [Note: P28 is the XC-90. The reinforced test is the previous one in the test series. The maximum Fz value in this test was 4.4kN.]

The test report concluded that:

> Following is needed to, as far as possible, avoid high neck loads in a vehicle with S80's inner space: The combination of activated shoulder and lap belt pretensioners together with a reinforced "green house." That means for instance re-enforced A-pillars, B-pillars, header, cant rails between A- and B-pillars and roof beam between the B-pillars.

These tests illustrate a successful crashworthiness test series examining the effect of design changes on rollover occupant protection. They make clear that a strong roof structure forms the cornerstone of the rollover occupant protection system. If the roof does not collapse it cannot harm the occupants seated under it. According to the discovery received to date, no such crashworthiness testing was conducted on the Hyundai Sonata platform that is the subject of this litigation.

Further XC90 design documents describe its performance in the FMVSS 216 quasi-static test. Volvo designed the roof not merely to pass the standard's requirements but to resist buckling and non-linear failure when deformed up to 10 inches.[93] The roof strength of the XC90 is specified to achieve a SWR of 3.5 within 2 inches of deformation and maintain that SWR to 8 inches of deformation at which point the SWR increases to 4.3 at 12 inches of deformation. The performance criteria also call for testing the roof at a greater roll angle of 45 degrees. This is 20 degrees greater than specified in FMVSS 216. The more lateral angle is indicative of loading that occurs in rollover accidents. These specifications are crucial in the design of a roof structure that is capable of a reasonable level of occupant protection. Roof crush must be managed over a wide range of loading conditions. Testing at 45 degrees of roll and requiring a SWR nearly three times higher than the FMVSS 216 requirement at twice the level of deformation required by the standard ensures that the roof will not catastrophically fail under rollover conditions.

Beyond requiring more stringent quasi-static tests, Volvo also prescribed the manner in which the XC90 roof should react during such testing. The design specifications state that the roof should not experience any localized deformations and that no failures, separations or collapses are allowed. These specifications are in recognition of the fact that merely designing a structure to pass a test is no guarantee of occupant safety. Rather, in addition to whatever

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[93] Reference Kane and DF submission to 5572 re: XC90 roof strength design criteria.

regulatory requirements it must satisfy the structure must be designed to protect the occupant from recognized sources of potential injury: collapsing, intruding and buckling roof structures.

The steel safety cage structure of the Volvo XC90 was the subject of a presentation by Volvo engineer Jonas Bernquist at the 2004 Great Designs in Steel seminar of the American Iron and Steel Institute.[94] Bernquist's presentation detailed the use of high- and ultra-high strength steel in the XC90. The presentation clearly shows how the XC90's exemplary performance was obtained. Through the selected use of high- and ultra-high strength steel, the XC90 offers high levels of occupant protection in all accident modes, including rollovers.

While the XC90 development data clearly describes how a vehicle can be designed to achieve structural rollover occupant goals, matched-pair drop tests of production and reinforced vehicles also clearly demonstrate that with a minimum of added weight roof strength can be dramatically increased in existing vehicles.[95],[96] With the addition of approximately 70 pounds of additional material, which was incorporated under the existing vehicle trim so that the post-modification vehicle looked identical to the unmodified vehicle, the roof intrusion was decreased by 77%. The average reduction in roof crush was approximately 8.5 inches.

Summary:

The injuries suffered by Misty Raley were a direct consequence of, and causally related to, the collapse and buckling of the Hyundai Sonata's defectively designed and unreasonably dangerous roof. The design defect in the roof structure is a result of its inadequate performance under dynamic loading conditions. Once the vehicle rolled over its lack of adequate upper interior padding contributed to the danger of the defectively designed roof and facilitated the injuries.

Other similar incidents show that in a variety of easily foreseeable accidents, the roof structure will buckle and collapse, leading to severe occupant injuries and death. Hyundai could have prevented the paralyzing injuries that resulted from this accident by adopting alternative design approaches, most of which were available and technologically and economically feasible at the time of the vehicle's design and, in fact, more than 60 years prior.

All of the conduct of the designer and manufacturer described above and the distributor in marketing the defective vehicle evidenced a reckless disregard and conscious indifference for the lives and safety of others, and were committed intentionally and were life threatening

To the extent possible, I am prepared to support my claims and provide direct testimony to counter all previously known defenses, and will further supplement this report should defense

[94] J Bernquist presentation "Safety Cage Design of the XC90," 2004 Great Designs in Steel presentation, available at www.autosteel.org.
[95] Herbst, B., et. al., "The Effect of Roof Strength on Reducing Occupant Injury in Rollovers", INTERNATIONAL Biomedical Sciences Instrumentation Symposium, April, 2005.
[96] Herbst, B., et. al., "Alternative Roof Crush Resistance Testing with Production and Reinforced Roof Structures", SAE 2002-01-2076.

disclosures or testimony present new theories or evidence or should new material pertinent to this case be received.

All of the opinions expressed herein are to a reasonable degree of engineering and biomechanical certainty.

The undersigned has prepared this report on behalf of the following experts at Xprts LLC: Dr. Carl Nash, Dr. Jack Bish, and Mr. Acen Jordan. Any of these experts will be able to testify subject to your designation.

Respectfully,

Donald Friedman

Enclosures:

Appendix 1 – Materials Reviewed
Appendix 2 – CFIR's 1st Submission to NHTSA Docket 2005-22143
Appendix 3 – CFIR's 2nd Submission to NHTSA Docket 2005-22143
Appendix 4 – Xprts' 1st Submission to NHTSA Docket 2005-22143
Appendix 5 – CFIR's 19th Submission to NHTSA Docket 1999-5572
Appendix 6 – CFIR's 21st Submission to NHTSA Docket 1999-5572
Appendix 7 – CFIR's 22nd Submission to NHTSA Docket 1999-5572
Appendix 8 – CFIR's 23rd Submission to NHTSA Docket 1999-5572

Attachment A – Donald Friedman's CV
Attachment B – Donald Friedman's List of Cases
Attachment C – Xprts Rate Schedule

MATERIALS REVIEWED

- Official Oklahoma Traffic Collision Report
- OU Medical Center Records for Misty Raley
- EMSA Medical Center Records for Misty Raley
- Valley Rehabilitation Hospital ecords for Misty Raley
- Xprts-LLC Vehicle Inspection on 2/16/2005
- Accident vehicle photographs provided by plaintiff's attorney
- Various sources of vehicle data including, but not limited to, VinDecoder, Autostats and equivalencies
- History of Rollovers video
- Notice of Proposed Rule Making – Roof Intrusion for Passenger Cars (Docket No. 2-6; Notice 4), April 5, 1971
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- Autoliv Final Report, Videos and Data of FMVSS 208 Rollover Crash Testing on Ford Explorer – Test Number B180219
- Inverted Drop Test of a Production-Roof 1994 Mazda B2300 Pickup
- Inverted Drop Test of a Reinforced-Roof 1994 Mazda B2300 Pickup
- Lateral Compression ("Claw") Test of a Production Roof 1994 Mazda B2300 Pickup
- Lateral Compression ("Claw") Test of a Reinforced-Roof 1994 Mazda B2300 Pickup
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- "Cab Roof Crush-Rollover Simulation," GM Inter-Organization Document from I. Arums to J.D. Green, June 27, 1984
- "Static Cab Crush Results," GM Internal Document from J.W. Moll to M.O. Ellis, November 18th, 1985.
- "Roof Strength Study," Ford Intra Company Memorandum from J.R. Weaver to H.G. Brilmeyer, July 8, 1968
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